AD-A163 431 EXPERIMENTS ON SOUND PROPAGATION OVER SLOPED BOTTOMS 1/1
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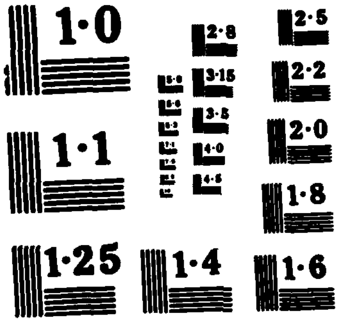

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EXPERIMENTS ON SOUND PROPAGATION OVER [illegible]
ANNUAL REPORT AND FINAL REPORT UNDER CONTRACT [illegible]

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14 November 1985

Annual Report: 1 July 1983 – 30 June 1984
Final Report: 1 July 1983 – 30 September 1984

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Prepared for:

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A163 431	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EXPERIMENTS ON SOUND PROPAGATION OVER SLOPED BOTTOMS		5. TYPE OF REPORT & PERIOD COVERED annual: 1 Jul 83 - 30 Jun 84 final: 1 Jul 83 - 30 Sep 84
		6. PERFORMING ORG. REPORT NUMBER ARL-TR-85-41
7. AUTHOR(s) Halvor Hobaek Chris T. Tindle T. G. Muir		8. CONTRACT OR GRANT NUMBER(s) N00014-83-K-0593
9. PERFORMING ORGANIZATION NAME AND ADDRESS Applied Research Laboratories The University of Texas at Austin Austin, Texas 78713-8029		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Department of the Navy Arlington, VA 22217		12. REPORT DATE 14 November 1985
		13. NUMBER OF PAGES 23
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

shallow water acoustics, acoustic waveguide,
modal propagation,
sound propagation

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Experiments to study sound propagation in a shallow water wedge ~~have been~~ were conducted in a tank. Results confirm the assumption of adiabatic normal mode theory that the mode shapes adjust continuously to the local water depth. Mode coupling, if it exists, is negligible. For upslope propagation, the energy of a mode traveling beyond its cutoff depth is directed into the bottom with negligible coupling to lower modes. For downslope propagation, the normal modes in a wedge propagate with curved wavefronts and not with the straight vertical wavefronts of simple adiabatic normal mode theory.

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20. (Cont'd)

In addition, normal modes not present at the source can be "captured" when the water depth is sufficient to support them. Keywords: (top i

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I. INTRODUCTION

Issues raised by recent theories of propagation into and out of a shallow water ocean wedge require precise and comprehensive measurements of the sound field in the water and the bottom for a variety of ranges and bottom slopes. These measurements are difficult in the ocean, and so we have performed a scaled model experiment in an indoor tank. Typical operating parameters are a water depth at the source of five wavelengths, ranges up to 500 wavelengths, and slopes up to 9°.

The objective of the experiment was to study propagation of normal modes in a smooth plane wedge. Early experimental work by Eby et al.[1] and theoretical work by Pierce[2] and Milder[3] suggested that normal modes far from cutoff behave adiabatically and adjust to the local water depth.

Recent numerical calculations by Jensen and Kuperman[4] suggested that as a normal mode passes upslope through its cutoff depth, its energy is transferred to the bottom with negligible coupling to lower modes.

Our results for a wider range of slopes and a greater number of modes are in agreement with the earlier work. A selection of our results is presented here and two new effects associated with propagation on slopes are described.

II. EXPERIMENTAL ARRANGEMENT

The ocean bottom in the model experiment is formed by a tray of sand 10 m long x 1 m wide x 20 cm deep. The sides and bottom of the tray are lined with random scatterers to eliminate specular reflections. The tray is suspended in the water and the slope and depth of the bottom can easily be varied. The sand has a sound speed of 1787 m/s, a density of 1.97 g/cc, and an attenuation of about 0.8 dB/wavelength.

The experiment was designed to use a line source operating in 10 cm of water at 80 kHz. There are six normal modes present in this case and the line source of seven elements can be shaded in phase and amplitude to generate individual normal modes. In reality, there is always some slight contamination from other modes but this does not lead to any difficulties in interpreting the results.

In some cases it is convenient to use a single point source rather than a line source; this is easily achieved by exciting an individual element of the source array.

The acoustic signals are received by a small probe hydrophone which can be positioned at any given range and then moved accurately in a vertical direction. The vertical movement is connected via a servomechanism to an analog chart recorder.

Data can be taken by two complementary methods. Analog chart recordings of signal level (in dB) as a function of depth can be obtained by simply operating the vertical movement of the probe hydrophone. In this method we use a gating technique described by Eby et al.[1] An electronic gate is set to detect the peak value of the signal within a small time interval. The time interval is chosen to coincide with the arrival of the mode under investigation, thus enabling the contamination from other modes to be minimized.

The second method of taking data is to fix the range and depth of the probe hydrophone and to digitize the entire waveform of the received signal. It is a simple matter to take recordings at various depths. These can be treated as if they were simultaneous recordings on a vertical array of hydrophones because the start of the digitization interval is accurately controlled.

It is well known[5] that signals from a vertical hydrophone array can be combined in a suitably weighted summation to allow extraction of the waveforms present in each individual normal mode. In the following figures the normal mode waveforms were obtained using this technique.

III. ANALOG RESULTS

Analog results of signal level as a function of depth have been taken for a variety of cases. Figure 1 shows results for downslope propagation at 1^{o} of bottom slope. The line source was shaded to generate modes 1, 2, and 3 successively, and the resulting analog traces are shown. It is clear that the modes have adjusted adiabatically to the local water depth of 22.9 cm. The small variation in the amplitude of modes 2 and 3 for different maxima of the same mode is consistent with contamination by other modes due to imperfect shading of the line source. It is not thought to be associated with coupling of energy between modes. The small oscillations in the bottom, some 35 dB below the maximum signal level in the water, represent the noise level of our measurements and are possibly due to sound propagating down the hydrophone support.

Figure 2 shows results for propagation upslope at 0.6^{o}. The line source in 10 cm water depth was shaded to preferentially excite mode 2. Figure 2(a) shows that mode 2 has adjusted to the local water depth of 4.8 cm. The field in the bottom falls off very rapidly. In Fig. 2(b) the water depth has decreased to 2.7 cm, and the "tail" of the mode falls off much more slowly in the bottom. In Fig. 2(c) the water depth is 2.4 cm, and mode 2 has passed beyond cutoff. There is now a substantial amount of energy propagating in the bottom. In Fig. 2(d) mode 2 has disappeared from the water column, and the field in the water is due to the small amount of mode 1 generated by the line source. The remaining energy of mode 2 is now propagating as a broad, strongly attenuated beam of sound whose axis has moved deeper into the bottom; this result is consistent with the numerical calculations of Jensen and Kuperman.[4] The results shown in Fig. 2 should be regarded as preliminary, as the origin of the small oscillations in the bottom is uncertain.

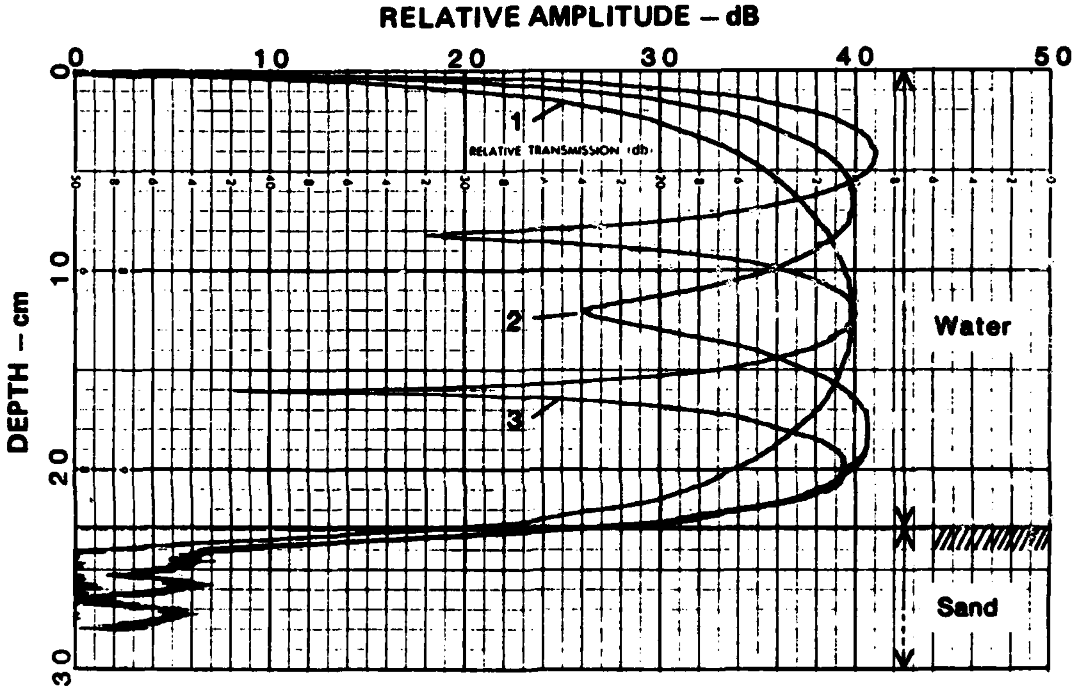

FIGURE 1

ANALOG RECORDS AT A RANGE OF 7.4 m FOR PROPAGATION DOWNSLOPE AT 1°

THE LINE SOURCE IN 10 cm WATER DEPTH WAS SHADED TO MODES 1, 2, AND 3 SUCCESSIVELY THE RECORDS SHOW THAT THE MODES HAVE ADJUSTED ADIABATICALLY TO THE LOCAL WATER DEPTH OF 22.9 cm

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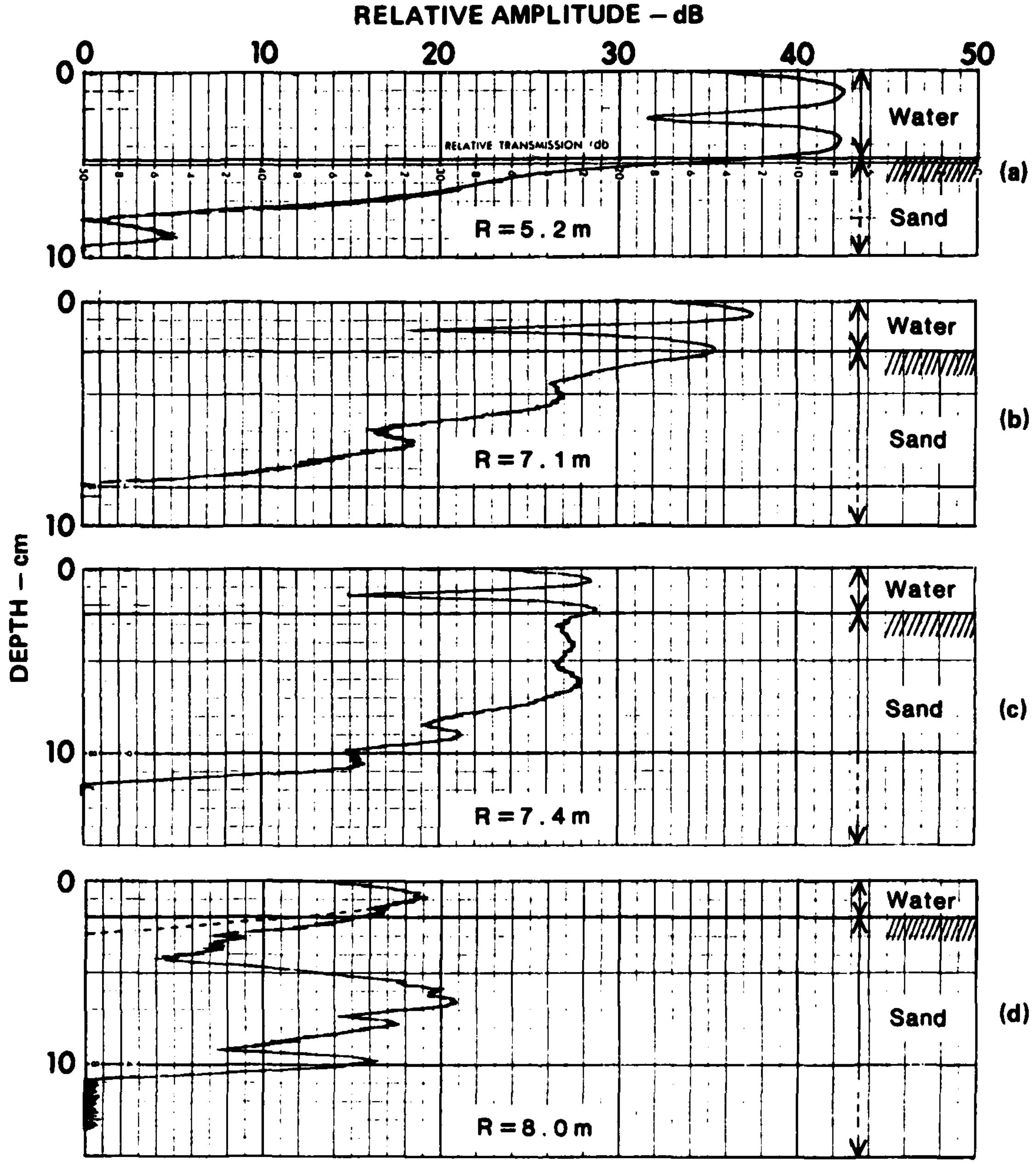

FIGURE 2
ANALOG RECORDS FOR PROPAGATION UPSLOPE AT 0.6°
THE LINE SOURCE WAS SHADED FOR MODE 2
RANGES ARE (a) WELL BEFORE CUTOFF, (b) JUST BEFORE CUTOFF,
(c) BEYOND CUTOFF, AND (d) WELL BEYOND CUTOFF
THE DASHED CURVE IN (d) INDICATES THE SEPARATELY MEASURED LEVEL OF MODE 1
WATER DEPTH AT EACH RANGE IS INDICATED ON THE FIGURES

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IV. WAVEFORM RESULTS

In constant water depth each individual normal mode travels with its own group velocity. Thus, if a point source emits a short pulse, the signal received downrange will be a series of possibly overlapping pulses associated with each mode. The individual normal mode waveforms can be extracted, an example of which is shown in Fig. 3(a). A point source at midwater depth was excited using a smoothly rising and falling pulse of approximately four cycles. The source element "rings" after the excitation is removed, so the decay of the pulse in the water is slower than its rise time. The waveform of mode 1 in Fig. 3(a) is very similar to that of the pulse emitted by the source.

The other mode waveforms in Fig. 3(a) show the well known features of normal mode propagation in isovelocity layers. In particular, (1) higher modes arrive progressively later due to their lower group velocities, (2) the pulses of higher modes are more dispersed due to their greater variation of group velocity with frequency, and (3) higher modes suffer progressively greater attenuation.

When the bottom is sloping, the above features are still present but the extent of each feature is strongly affected by even a small slope, as can be seen by comparing Figs. 3(a) and 3(b). Figure 3(b) shows the waveform obtained at the same range as Fig. 3(a) for downslope propagation at 1° of bottom slope. The relative arrival times of the higher modes are now much reduced. For example, the time interval between the peaks of modes 1 and 4 is reduced from 0.25 ms to 0.11 ms. The dispersion in the higher modes is also much reduced.

Another important effect of the slope is the severely reduced attenuation of the higher modes. Mode 6 is easily observed at 1° of bottom slope and yet for constant water depth, mode 6 is barely present at this range and could not be detected at greater ranges.

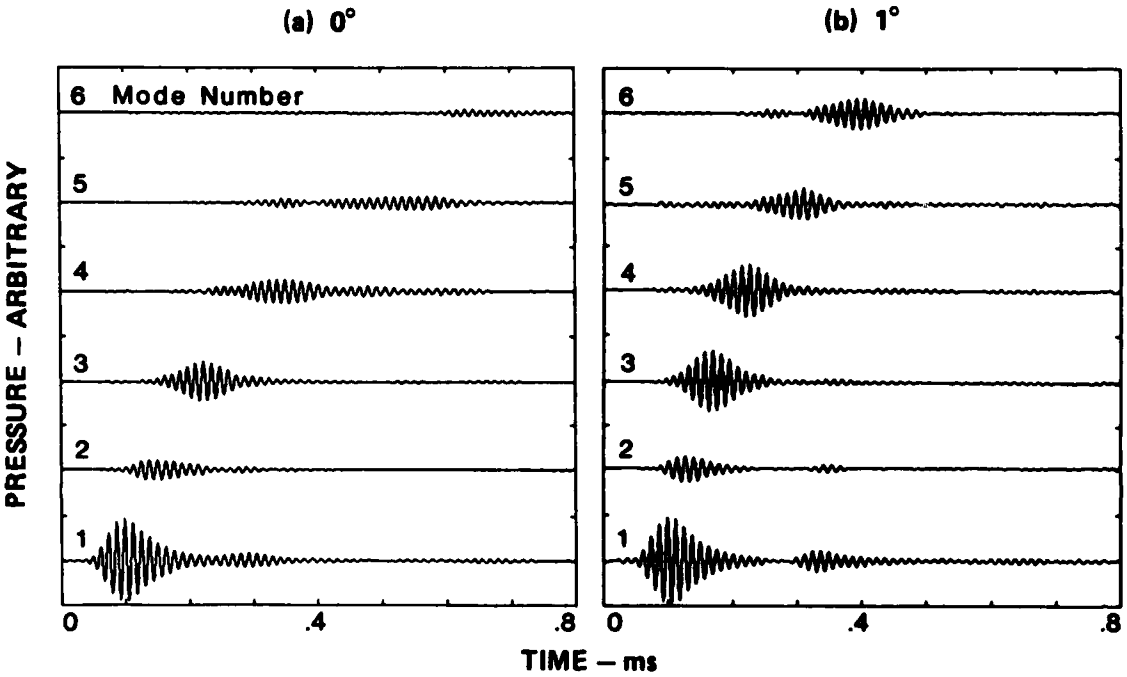

FIGURE 3
NORMAL MODE WAVEFORMS AT BOTTOM SLOPES OF (a) 0° AND (b) 1°
AT A RANGE OF 7 m USING A SINGLE SOURCE AT MIDWATER DEPTH
WATER DEPTH AT THE SOURCE IS 10 cm AND PROPAGATION IS DOWNSLOPE
THE SMALL SECOND ARRIVALS PRESENT IN MODE 1 (AND VERY SLIGHTLY
IN MODE 2) ARE REFLECTIONS FROM THE TANK WALL AND SHOULD BE IGNORED

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The above features of downslope propagation are all consistent with simple adiabatic normal mode theory. As the water depth increases, the group velocity should decrease, the dispersion should be reduced, and the attenuation should be reduced as the "exponential tail" of the mode penetrating into the bottom decreases.

We have taken data at bottom slopes of up to 9^{0}, and the above effects continue to be observed. Figure 4(c) shows normal mode waveforms at 9^{0}. The source waveform used was a very sharply defined four-cycle pulse, very similar to that shown for mode 1, which propagates with negligible dispersion. The time separation between successive modes is seen to be very small for large bottom slopes.

The mode waveforms of Fig. 4(c) were obtained from the hydrophone data of Fig. 4(a). The first part of the waveforms of Fig. 4(a) are shown on an expanded item scale in Fig. 4(b) to illustrate the time delay which occurs for the deeper hydrophones due to the sloping bottom. The time delay between top and bottom hydrophone waveforms for Figs. 4(a) and (b) is 0.035 ms and corresponds to 2.8 wavelengths.

The first arrival of the signals has a delay which is consistent with spherical spreading from the point source. In performing the extraction of the mode waveforms, it was necessary to shift the hydrophone waveforms in time to synchronize them. The fact that the extraction of the mode waveforms is then successful shows that the normal modes do not propagate as wavefronts which are simultaneous at all depths. Instead, they propagate as spherical wavefronts. This is in contrast to simple adiabatic normal mode theory which assumes that normal modes propagate as vertical wavefronts.

An interesting new effect is illustrated in Fig. 5, which shows mode waveforms at a range of 4 m and slopes of 1^{0} and 3^{0}. The source is placed near the surface in only 5 cm of water. This water depth can support only three normal modes but we see in Fig. 5(b) that four normal modes are present in the received signal. It is clear that energy

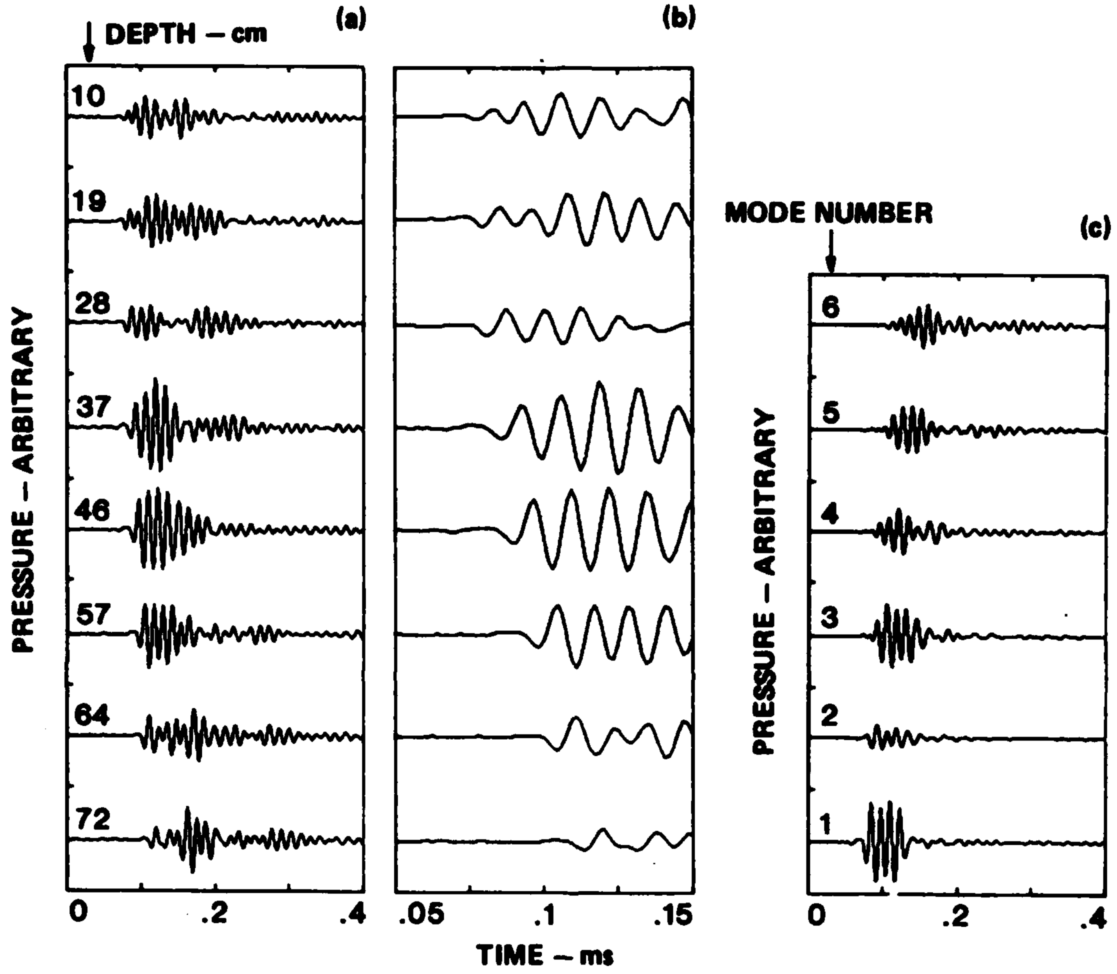

FIGURE 4
HYDROPHONE WAVEFORMS AND NORMAL MODE WAVEFORMS
AT A RANGE OF 4.5 m AND A SLOPE OF 9°
WATER DEPTH AT THE SOURCE IS 10 cm WITH THE SOURCE AT MIDWATER DEPTH AND PROPAGATION IS DOWNSLOPE
(a) WAVEFORMS AT SUCCESSIVE DEPTHS AS INDICATED, (b) SAME AS (a) BUT WITH EXPANDED TIME SCALE TO SHOW THE DELAY BETWEEN SIGNALS ARRIVING AT THE TOP AND SUCCESSIVELY LOWER HYDROPHONES,
(c) MODE WAVEFORMS EXTRACTED FROM THE HYDROPHONE WAVEFORMS OF (a)

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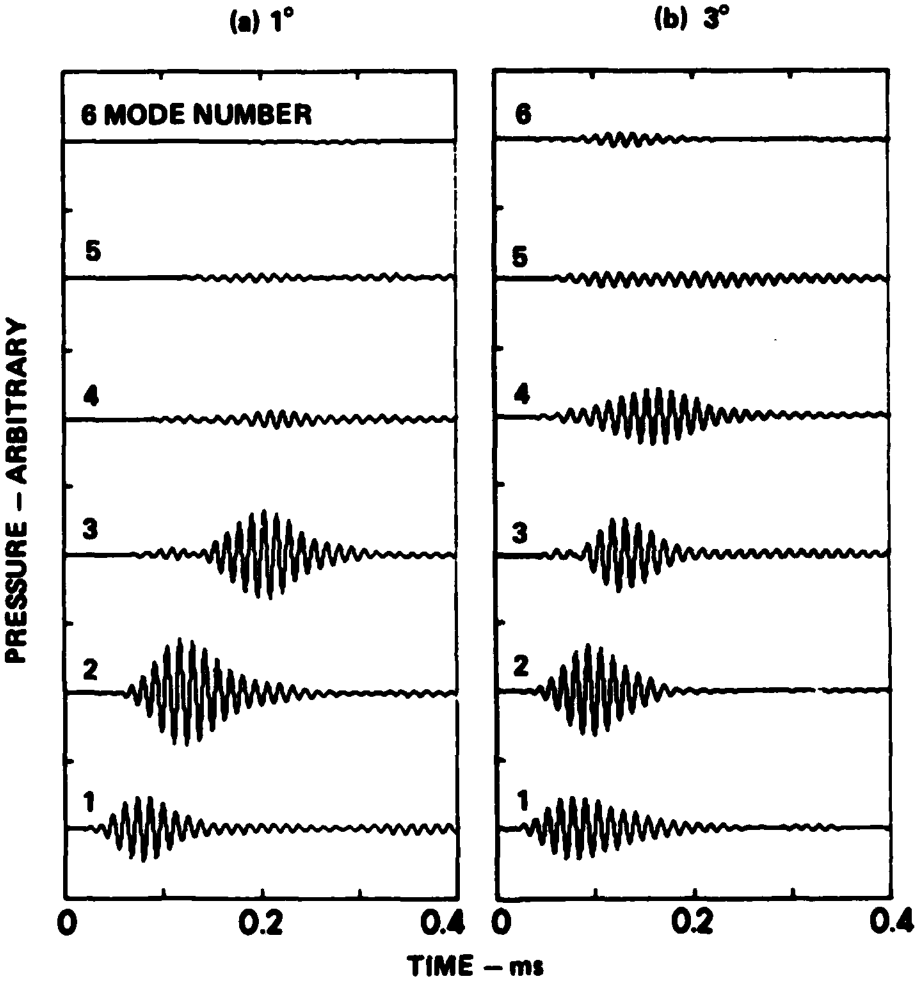

FIGURE 5
NORMAL MODE WAVEFORMS AT BOTTOM SLOPES OF (a) 1° AND (b) 3° AT RANGE OF 4 m
THE SOURCE IS NEAR THE SURFACE IN 5 cm OF WATER AND PROPAGATION IS DOWNSLOPE

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coupling into mode 4 is not present at the source as a discrete mode. Therefore, some of the energy which is usually associated with the continuum can be trapped when the water depth is sufficient to support another discrete mode. Thus a normal mode which is not present at the source can become "captured" as the water depth increases. This effect had been noted earlier in the theoretical calculations of Tindle and Deane.[6]

V. SUMMARY AND CONCLUSIONS

1. The experiment has confirmed the assumption of adiabatic normal mode theory that, for a smooth plane wedge, the mode shape adjusts continuously to the local water depth. The group velocities of the modes are also consistent with the adiabatic assumption.

2. The experiment has shown that, as a mode passes through cutoff in upslope propagation, its energy enters the bottom as a beam, and that there is negligible coupling to lower modes.

3. Mode coupling effects, if they exist, are very small.

4. The normal modes propagate downslope as curved wavefronts, and not as the vertical wavefronts of simple adiabatic normal mode theory.

5. Modes not trapped in the water depth at the source may be "captured" when the water depth increases.

ACKNOWLEDGMENT

H. Hobaek is grateful for partial support from the Norwegian Council for Science and the Humanities.

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